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The stellar mass spectrum in warm and dusty gas: deviations from Salpeter in the Galactic centre and in circumnuclear starburst regions

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ABSTRACT

Understanding the origin of stellar masses is a key problem in astrophysics. In the solar neighbourhood, the mass distribution of stars follows a seemingly universal pattern. In the centre of the Milky Way, however, there are indications for strong deviations and the same may be true for the nuclei of distant starburst galaxies. Here we present the first numerical hydrodynamical calculations of stars formed in a molecular region with chemical and thermodynamic properties similar to those of warm and dusty circumnuclear starburst regions. The resulting initial mass function is top-heavy with a peak at $\sim$15 $M_{\odot}$, a sharp turn-down below $\sim$7 $M_{\odot}$ and a power-law decline at high masses. We find a natural explanation for our results in terms of the temperature dependence of the Jeans mass, with collapse occurring at a temperature of $\sim$100 K and an H_2 density of a few $\times 10^5$ cm^{-3}, and discuss possible implications for galaxy formation and evolution.

Key words: equation of state – hydrodynamics – turbulence – stars: formation – Galaxy: centre – galaxies: starburst.

1 INTRODUCTION

Identifying the physical processes that determine the masses of stars and their statistical distribution, the initial mass function (IMF), is a fundamental problem in star formation research. It is central to much of modern astrophysics, with implications ranging from cosmic reionization and the formation of the first galaxies, over the evolution and structure of our own Milky Way, down to the build-up of planets and planetary systems.

Near the Sun the number density of stars as a function of mass has a peak at a characteristic stellar mass of a few tenths of a solar mass, below which it declines steeply, and for masses above one solar mass it follows a power law with an exponent $\mathrm{d}N/\mathrm{dlog}\, m \propto m^{-1.3}$. Within a radius of several kpc this distribution shows surprisingly little variation (Salpeter 1955; Scalo 1998; Kroupa 2001, 2002; Chabrier 2003). This has prompted the suggestion that the distribution of stellar masses at birth is a truly universal function, which often is referred to as the Salpeter IMF, although note that the original Salpeter (1955) estimate was a pure power-law fit without characteristic mass scale.

On the other hand, there is increasing evidence that the IMF close to the centre of our Milky Way (Stolte et al. 2002, 2005; Nayakshin & Sunyaev 2005; Paumard et al. 2006) and the neighbouring Andromeda galaxy (Bender et al. 2005) is dominated by massive rather than low-mass stars. For the circumnuclear starburst regions in more distant galaxies, very similar IMF deviations are subject to continuing debate (e.g. Scalo 1990; Elmegreen 2005). However, no conclusion has yet been reached, and it appears timely to examine the problem from a theoretical point of view.

We approach the problem by means of self-consistent hydrodynamical calculations of fragmentation and star formation in interstellar gas where chemical and thermodynamical properties are described by a realistic equation of state (EOS). We focus on the most extreme environmental conditions such as occur in the nuclear regions of massive star-forming spiral galaxies. There the inferred dust and gas temperatures, gas densities and star formation rates typically exceed the solar-neighbourhood values by factors of 3, 10 and $\geqslant$100, respectively (e.g. Ott et al. 2005; Israel 2005; Aalto et al. 2002; Spinoglio, Andreani & Malkan 2002). Consequently, it has long been speculated that such conditions lead to deviations from the Salpeter IMF (e.g. Scalo 1990; Elmegreen 2005).

2 MODEL

Stars and star clusters form through the interplay between self-gravity on the one side and turbulence, magnetic fields and thermal pressure on the other (for recent reviews see Larson 2003; Mac Low & Klessen 2004; Ballesteros-Paredes et al. 2006a). The supersonic turbulence ubiquitously observed in interstellar gas clouds

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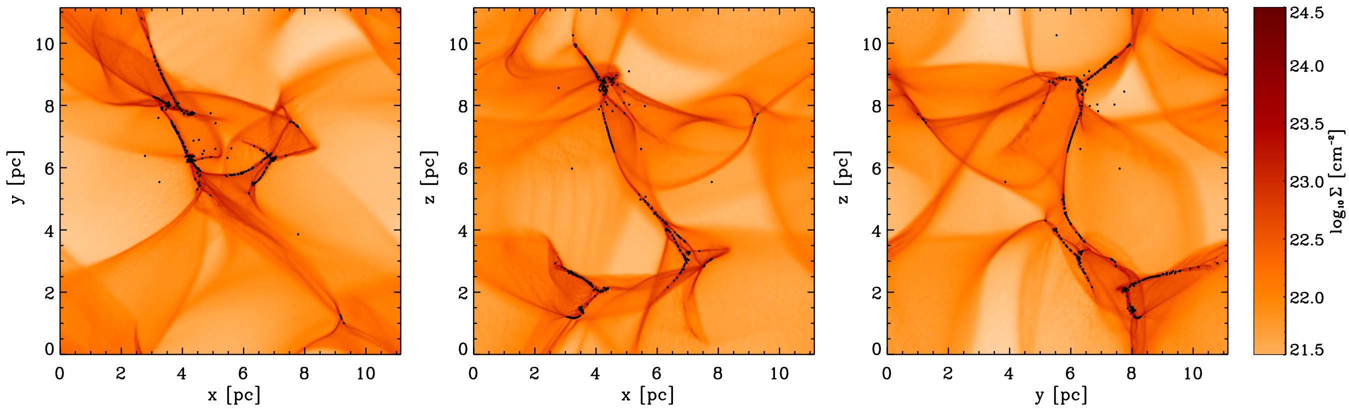

Figure 1. Column density distribution of the gas projected along the three principal axes of the system after 3.5 million years of evolution when 15 per cent of the gas is converted into protostars (sink particles). Their location is indicated by black dots.

can create strong density fluctuations with gravity taking over in the densest and most massive regions. Collapse sets in to build up stars and star clusters. Turbulence plays a dual role. On global scales it provides support, on local scales it provokes collapse. Stellar birth is thus intimately linked to the dynamic behaviour of the parental gas cloud, which governs when and where star formation sets in (as illustrated in Fig. 1).

The chemical and thermodynamic properties of interstellar clouds play a key role in this process. In particular, the value of the polytropic exponent γ, when adopting an EOS of the form $P \propto \rho^{\gamma}$, strongly influences the compressibility of density condensations as well as the temperature of the gas. The EOS thus determines the amount of clump fragmentation, and so directly relates to the IMF (Vázquez-Semadeni, Passot & Pouquet 1996) with values of γ larger than unity leading to little fragmentation and high mass cores (Li, Klessen & Mac Low 2003; Jappsen et al. 2005). The stiffness of the EOS in turn depends strongly on the ambient metallicity, density and infrared background radiation field produced by warm dust grains. The EOS thus varies considerably in different galactic environments (see Spaans & Silk 2000, 2005, for a detailed account).

For the circumnuclear starburst regions that are the subject here we assume a cosmic ray ionization rate of 3×10^{-15} s^{-1}, solar relative abundances (Asplund, Grevesse & Sauval 2005; Jenkins et al. 2004) and an overall metallicity of two times solar (Barthel 2005). A velocity dispersion $\Delta V_{\rm tur} = 5$ km s^{-1} is adopted to take the larger input of kinetic energy (e.g. through supernovae) into account. The dust temperature inside the model clouds is set by a fiducial background star formation rate of $100\,{\rm M}_{\odot}$ yr^{-1} kpc^{-2} which causes dust grains to be at temperatures of about $T_d = 30$–90 K, depending on the amount of shielding. Gas temperatures range from $T_g = 40$–140 K, over a density range of 10^4–10^7 cm^{-3}. These values are consistent with gas and dust temperatures determined for circumnuclear starburst regions (Klaas et al. 1997; Aalto et al. 2002; Spinoglio et al. 2002; Ott et al. 2005; Israel 2005).

Fig. 2 shows the resulting polytropic exponent as a function of density. The main feature is the $\gamma > 1$ peak around $n = 10^4$ cm^3. This peak implies that the gas warms up as it is compressed and it is caused mainly by strong photon trapping in opaque H_2O and CO lines in the metal-rich nuclear gas. That is, the large optical depth in the cooling lines suppresses the cooling efficiency. Also, warm dust ($T > 40$ K), heated by the ambient stars, causes H_2O collisional de-excitation heating through far-infrared pumping (Takahashi, Hollenbach & Silk 1983; Spaans & Silk 2005), which adds to the gas-dust heating.

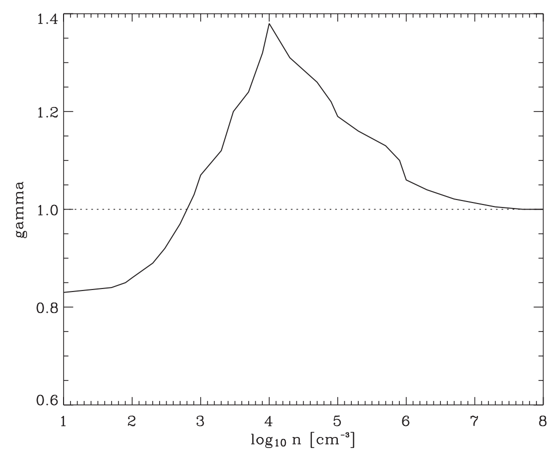

Figure 2. Starburst EOS adopted from Spaans & Silk (2005).

The cosmic-ray heating rate is elevated by a high supernova rate, as expected for nuclear starburst regions (Bradford et al. 2003).

Adopting this EOS we follow the dynamical evolution of the star-forming gas using smoothed particle hydrodynamics (SPH). This is a Lagrangian method to solve the equations of hydrodynamics, where the fluid is represented by an ensemble of particles, and flow quantities are obtained by averaging over an appropriate subset of SPH particles (Monaghan 2005). The method is able to resolve high density contrasts as particles are free to move, and so the particle concentration increases naturally in high-density regions. The performance and convergence properties of SPH are well understood and tested against analytic models and other numerical schemes in the context of astrophysical flows (see, e.g. Mac Low et al. 1998; Lombardi et al. 1999; Klessen, Heitsch & Mac Low 2000; O'Shea et al. 2005; Ballesteros-Paredes et al. 2006a). Artificial fragmentation can be ruled out, as long as the mass within one smoothing volume remains less than half the critical mass for gravitational collapse (Bate & Burkert 1997; Hubber, Goodwin & Whitworth 2006). We use the publically available parallel code GADGET (Springel, Yoshida & White 2001). It is modified to replace high-density cores with sink particles (Bate, Bonnell & Price 1995) that can accrete gas from their surroundings while keeping track of mass and momentum. This enables us to follow the dynamic evolution of the system over many local free-fall time-scales. We identify sink particles as the direct

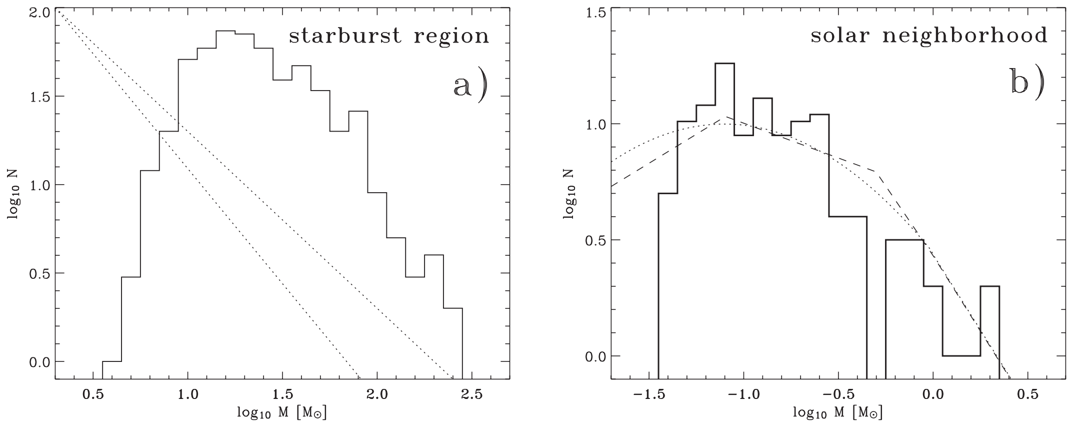

Figure 3. (a) Mass spectrum of gravitational condensations in the starburst calculation at a time when 15 per cent of the gas is converted into collapsed objects (which we identify as direct progenitors of individual stars). To guide the eye, we indicate a slope −1.0 and the Salpeter slope −1.3 with dotted lines. The mass function in our simulated starburst environment shows a broad peak in the range 10–25 $M_\odot$ and falls off for larger masses. It is thus top-heavy compared to the IMF in the solar neighbourhood (Salpeter 1955; Kroupa 2002; Chabrier 2003). (b) Mass spectrum of collapsed objects in a calculation focusing on nearby molecular clouds (see Jappsen et al. 2005). It agrees well with the IMF in the solar vicinity. For comparison we overplot the functional forms proposed by Kroupa (2002) with dashed lines and by Chabrier (2003) with dotted lines. Our two calculations differ mainly in the adopted EOS, i.e. in the chemical and thermodynamic state of the star forming gas, other parameters are comparable.

progenitors of individual stars. For a more detailed account of the method and a discussion of its convergence properties we refer the reader to Klessen et al. (2000) and Jappsen et al. (2005).

We focus on a cubic volume of 11.2 pc in size, which contains 80 000 $M_\odot$ of gas and has an initial mean particle density $n = 10^3\,\mathrm{cm}^3$ at a temperature of 21 K. Above the characteristic density $n = 10^4\,\mathrm{cm}^{-3}$ where γ is at a maximum, the temperature quickly reaches values of ∼100 K. This set-up is chosen to describe the typical environment within the central regions of an actively star-forming galaxy such as our own Milky Way or NGC 253. In such galaxies, high-density gas with $n > 10^5\,\mathrm{cm}^{-3}$, as traced by HCN, typically has a filamentary structure with very low filling factor, while the bulk of the gas is at $n \approx 10^3\,\mathrm{cm}^{-3}$ (Morris & Serabyn 1996; Hüttemeister et al. 1993; Israel & Baas 2003), exactly as found at the end of our simulation (see Fig. 1). We stop the calculation at a star formation efficiency (SFE) ≈15 per cent, when roughly 1/6 of the total gas mass has turned into gravitationally collapsed condensations (i.e. sink particles, which we identify as direct progenitors of individual young stars).

Throughout the simulation we drive turbulence continuously on large scales, with wave numbers k in the range $1 \leqslant k \leqslant 2$ (see Mac Low 1999) to yield a constant turbulent Mach number $\mathcal{M}_{\rm rms} \approx 5$. The particle number is $N = 8\,000\,000$. This is thus one of the highest-resolution star formation calculations performed with SPH, with a total CPU time of 8×10^4 h. The critical density for sink particle formation is $n_c = 10^7\,\mathrm{cm}^{-3}$, with a sink particle radius of 0.015 pc. The mass of individual SPH particles is $m = 0.01\,M_\odot$, which is sufficient to resolve the minimum Jeans mass in the system $M_{\rm J} \approx 1.5\,M_\odot$. Except for the EOS and the particle number, the numerical set-up is identical to the study by Jappsen et al. (2005). We have performed a second run for a region of 5.7 pc with four times less mass, eight times fewer particles and a sink particle radius of 0.02 pc that has reached a SFE ∼36 per cent.

3 RESULT AND PHYSICAL INTERPRETATION

We find that in the considered star-forming region, the mass spectrum of collapsed objects is biased towards high masses. The resulting IMF has a broad peak at ∼15 $M_\odot$ followed by an approximate power-law fall-off with a slope in the range −1.0 to −1.3. Furthermore, there is a clear deficit of stars below 7 $M_\odot$. This is illustrated in Fig. 3(a). We contrast this finding with the result from a simulation appropriate for the physical conditions in star-forming regions near the Sun (from Jappsen et al. 2005), where γ changes from 0.7 to 1.1 at an H_2 density of a few $\times 10^5\,\mathrm{cm}^{-3}$. As expected, Fig. 3(b) shows a mass spectrum that is very similar to the IMF in the solar neighbourhood (Kroupa 2002; Chabrier 2003). These striking differences are caused by the very disparate chemical and thermodynamic state of the star-forming gas in the two simulations, as all other parameters are very similar. Our results thus support the hypothesis that for extreme environmental conditions as inferred for the centres of most spiral galaxies or more general for infrared–luminous circumnuclear starburst regions the IMF is indeed expected to be top-heavy.

There is a natural explanation for our results in terms of the temperature dependence of the Jeans mass $M_{\rm J}$. Compared to a mean temperature of 10 K for dense molecular gas in the Milky Way, gravitationally collapsing gas in our simulations has a temperature of ∼100 K and an H_2 density of a few $\times 10^5\,\mathrm{cm}^{-3}$. As the critical mass for gravitational collapse scales as $M_{\rm J} \propto T^{1.5}$, this boosts $M_{\rm J}$ from 0.3 $M_\odot$ at 10 K to about 10 $M_\odot$ at 100 K (see also Klessen et al. 2000; Bonnell, Clarke & Bate 2006). This temperature may seem high, but is quite consistent with molecular cloud observations in the Galactic centre (e.g. Hüttemeister et al. 1993) or with high-density ($n > 10^4\,\mathrm{cm}^{-3}$) NH_3 data in the starburst centre of NGC253 (Ott et al. 2005). We also note that this Jeans mass scaling argument is supported by recent observations in more nearby high-mass star-forming regions. For example, in M17 at a distance of 1.6 kpc from the Sun, the mass spectrum of prestellar cores, which are the direct progenitors of individual stars, peaks at at ∼4 $M_\odot$ at an ambient temperature of 30 K (Reid & Wilson 2006). This is well above the corresponding peak in low-mass star-forming regions (e.g. Motte, André & Neri 1998).

4 DISCUSSION

Our mass spectrum is in good agreement with the IMF estimates in the Galactic centre by Stolte et al. (2002, 2005), Nayakshin &

Sunyaev (2005), and Paumard et al. (2006). For example, Stolte et al. (2002, 2005) find for the Arches cluster a clear deficit of stars below 7 $M_\odot$. This is consistent with our result in the sense that the ambient densities and temperatures found in the Galactic centre are similarly elevated (Helfer & Blitz 1996) as in the circumnuclear starburst environment we consider. We stress that the turn-down in our model IMF at masses below 10 $M_\odot$ is a direct consequence of the stiff EOS for densities n above a few $\times 10^3$ cm^{-3} through the Jeans mass temperature dependence, and is not caused by resolution effects. Our two simulations resolve masses down to $\sim$2 $M_\odot$ and $\sim$1 $M_\odot$, respectively, and our least massive stars (i.e. sink particles) are well above this limit. Rather, the effective Jeans mass at $T \sim$ 100 K and densities of $\sim 10^5$–10^6 cm^{-3} prevent the formation of low-mass stars.

When interpreting our simulation results, there are several caveats that need to be kept in mind. First, our numerical model does not include shear. Strong shear motions may mimic the EOS effects discussed here, as shear adds stability and thus requires larger Jeans masses for collapse to occur. However, the Arches cluster is bound. Thus the Galactic centre shear field cannot play a dominant role in the inner parts of the cluster. Secondly, our numerical model does not take the effects of magnetic fields into account, which may be of considerable strength in the Galactic centre (Yusef-Zadeh & Morris 1987, but also see Roy 2004 for lower estimates). However, even if there is a rough equipartition between kinetic and magnetic energy, the chemical and thermodynamic properties of the gas are not strongly affected. Our results will still hold at least qualitatively, in the sense that an extreme environment leads to deviatiations from the standard Salpeter IMF. Thirdly, the use of sink particles does not permit us to resolve close binary systems. Massive stars in the solar vicinity are almost always members of a binary or higher-order multiple stellar system (e.g. Vanbeveren, De Loore & Van Rensbergen 1998). If this trend holds also for starburst environments, then the peak of the stellar IMF will lie below the value reported here. For instance, if each unresolved sink particle in our calculation separates into a binary star, in a statistical sense our mass spectrum needs to be shifted to lower masses by a factor of 0.5. Finally, protostellar feedback may locally affect the accretion on to individual protostars. In this case the mass content of the sink particle may only poorly reflect the mass that ends up in a star. However, even in the extreme case that half the mass is removed by feedback during collapse (for estimates, see Yorke & Sonnhalter 2002; Krumholz, McKee & Klein 2005), deviations from the standard IMF will still persist.

For typical molecular clouds in the Milky Way, less than a few per cent of their mass takes part in star formation (e.g. Myers et al. 1986) and this fraction goes up by a factor of a few for cluster-forming cores (e.g. Lada & Lada 2003). A number of observations (Paglione, Jackson & Ishizuki 1997; Mooney & Solomon 1988) indicate that starburst systems such as NGC253 and M82, and luminous infrared galaxies in general, have a larger fraction of their interstellar gas mass at high densities (Gao & Solomon 2004). Consequently, their SFEs are up by as much as an order of magnitude. Our simulations cover this range and the statistics of our mass spectra do not change above a SFE $\sim$10 per cent in both runs. Hence, the precise SFE that pertains to a starburst environment does not influence our results as long as it is larger than 10 per cent.

The computed star formation rate (SFR), defined as the change in mass of the sink particles with time, is typically 860 $M_\odot$ yr^{-1} kpc^{-2} for a SFE $>$10 per cent and when normalized to a surface area of 1 kpc^2, which is roughly the size scale of the nuclear region inside a starburst galaxy. This number lies well within the fiducial range of 50–1000 $M_\odot$ yr^{-1} kpc^{-2} inferred for most starburst systems (e.g. Kennicutt 1998; Scoville & Wilson 2004).

When turning to distant starburst galaxies in the early Universe, the low-mass cut-off at 7 $M_\odot$ seen in the simulated local starburst region seems at first glance difficult to reconcile with the mass-to-light ratio and the stellar population synthesis models inferred from global observations (Kaufmann et al. 2003). However, we emphasize again that we are focusing on an extreme case and on a clearly localized, isolated region only. In reality these extreme (warm and dusty) environmental conditions will not apply to all regions inside a starburst galaxy. There will be pockets of colder gas with different ($\gamma < 1$) EOS that are less exposed to radiation (Spaans & Silk 2000) and that behave like Galactic star-forming regions. Under these conditions the studies by Jappsen et al. (2005) and Larson (2005) indicate that a normal, Salpeter-like IMF results. This also suggests that the relative contribution of the extreme IMF found in this work can be connected directly to the observations. The fraction of molecular gas at densities $>10^4$ cm^{-3} that enjoys temperatures larger than 50 K should be a strong indicator of deviations from a Salpeter IMF. Future work will address the issue of stellar population matching and will compare our results with observed M/L ratios and warm, high density gas mass estimates.

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